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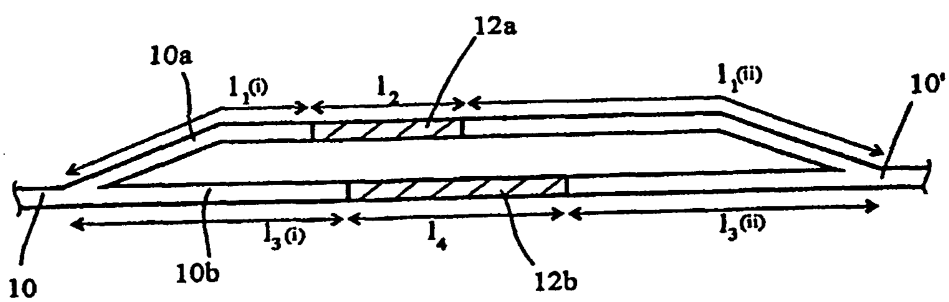

(57) Abstract

The application describes a temperature stable integrated optical device which is substantially insensitive to temperature variations. The device, such as an interferometer, includes sub–sections (12a, 12b) of a different light transmissive material within the optical pathways (10a, 10b). The relative lengths of the two different material waveguides can be selected so as to achieve temperature insensitivity. A suitable balance is to ensure that the ratio of the difference in sub–path lengths of the first and second pathways is equal to the ratio of the respective refractive index gradient with temperature of the materials used. Suitable materials are silicon and silicon nitride.

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TEMPERATURE STABLE INTEGRATED OPTICAL DEVICE

TECHNICAL FIELD

This invention relates to temperature stable integrated optical devices such as integrated silicon waveguides for use in optical circuits and the modulation of light within those circuits.

BACKGROUND ART

Interferometers are important elements of optical circuits, and are used, for example, to provide a wavelength selection function, routing functions, analysis functions, interrogation functions, switching etc. Such devices work by providing two pathways for the incoming light which are of slightly different optical length. The two pathways then recombine, at which point interference effects occur and wavelength selection, for example, is achieved.

A major difficulty with fabricating such interferometers is that silicon has a refractive index that varies with temperature, as do most optical materials. Thus, devices using imbalanced optical paths with a nominally fixed length will have a transmission characteristic which will vary with temperature.

This temperature variation is commonly alleviated either by using thermo-electric coolers or by heating the entire optical component to a

specified temperature. Thermo-electric coolers are expensive, whilst it is often undesirable to heat the component.

DISCLOSURE OF INVENTION

According to the present invention, there is provided an integrated optical device comprising first and second associated optical pathways, at least the first pathway including at least two sub-sections of first and second different transmissive materials, the different materials exhibiting a different temperature dependence of refractive index, the lengths of the pathways and of sub-sections being selected such that the device is substantially temperature insensitive.

Essentially, through the use of two different materials, the invention allows the difference in thermal dependence between the two materials in the first pathway to be exploited so as to match the composite thermal dependence of the first pathway to the second.

It is possible for the second pathway to be of a single material, but it is usually easier to design the device if the second pathway also includes a sub-section of a different transmissive material.

Suitable materials are silicon and silicon nitride, although the present invention is not limited to that combination of materials. Likewise, simplicity of design can be achieved by including only two sub-pathways in the relevant pathway.

The most straightforward device is likely to include two sub-sections on two pathways, and therefore the remainder of this Application will include description of such a device. However, the principle of temperature compensation disclosed herein can be employed if desired in more complex

arrangements.

A suitable method of selecting the lengths of pathways and sub-pathways to achieve temperature insensitivity is to ensure that the ratio of the difference in length of sub-sections formed of the first material to the difference in length of sub-sections formed of the second material is equal to the ratio of the respective refractive index gradient with temperature of the materials used. This can also be expressed as in equation 7 below.

The device is preferably an interferometer. However, the invention is applicable to any device using two or more nominally fixed length pathways, such as an arrayed waveguide grating.

Other preferred features of the invention will be apparent from the following description and the subsidiary claims of the specification.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the present invention will now described, by way of example, with reference to the accompanying Figures, in which;

Figure 1 is a top view of an interferometer illustrating the present invention;

Figure 2 is a vertical section through the waveguides of Figure 1 showing the intersection in materials;

Figure 3 is a top view corresponding to Figure 2; and

Figure 4 shows an arrayed waveguide grating according to the

present invention.

BEST MODE OF CARRYING OUT THE INVENTION

It should be noted that for convenience of description, terms such as "lateral", "vertical", "side", "top" etc. used in the specification refer to directions relative to a device in the orientation shown in the accompanying drawings. The terms should not, however, be interpreted as restricting the scope of the claimed invention which may in practice be used in any orientation.

Figure 1 shows schematically a path imbalanced interferometer constructed according to the present invention. An optical pathway 10 divides into sub-pathways 10a and 10b before finally recombining as 10'. Sub-pathways 10a and 10b are of different physical lengths and are intended to provide a different optical path length to light which eventually recombines at 10' to interfere and provide wavelength selection. Such structures can be constructed as set out in (for example) our earlier application WO95/08787.

In the preferred embodiment illustrated, the optical pathway 10, 10a, 10b, 10' is generally formed of silicon. However, sub-pathway 10a includes a short section 12a of silicon nitride, and (likewise) sub-pathway 10b includes a sub-section 12b of silicon nitride. Silicon nitride has a different refractive index and a different temperature co-efficient of refractive index as compared to silicon.

As noted in Figure 1, the total length of silicon waveguide in sub-pathway 10a is equal to the sum of the lengths $l_1(i)$ and $l_1(ii)$, whilst the length of silicon nitride waveguide 12a is equal to l_2.

Within sub-pathway 10b, the total length of silicon waveguide is equal to the sum of the lengths l_3(i) and l_3(ii), and the length of silicon nitride waveguide 12b is equal to l_4. For simplicity, the aggregate values l_1 and l_3 will be used to denote the total length of silicon waveguide in sub-pathways 10a and 10b respectively.

In this case, the total effective path difference will be;

$$OPD = n_1 l_1 + n_2 l_2 - n_1 l_3 - n_2 l_4 \qquad [1]$$

where n_1 and n_2 are the refractive indices of silicon and silicon nitride respectively. If we assume that

$$\frac{dl_x}{dT} = 0 \qquad \{\text{for } x=1 \text{ to } 4\}, \qquad [2]$$

which is reasonable for the materials considered, this gives

$$\frac{dOPD}{dT} = l_1\frac{dn_1}{dT} + l_2\frac{dn_2}{dT} - l_3\frac{dn_1}{dT} - l_4\frac{dn_2}{dT} \qquad [3]$$

where $\frac{dn_1}{dT}$ and $\frac{dn_2}{dT}$ are the temperature dependencies of the refractive indices of silicon and silicon nitride respectively.

If we set $\frac{dOPD}{dT} = 0$, i.e. requiring no change of refractive index with temperature, and rearranging, we have;

$$0 = (l_1 - l_3)\frac{dn_1}{dT} + (l_2 - l_4)\frac{dn_2}{dT} \qquad [4]$$

This can be rewritten as

$$(l_1 - l_3)\frac{dn_1}{dT} = (l_4 - l_2)\frac{dn_2}{dT} \qquad [5]$$

In general, the temperature dependence of refractive index with temperature is substantially linear, allowing us to introduce an arbitrary coefficient *r*, being the ratio of the temperature coefficients for the two materials. Thus,

$$\frac{dn_1}{dT} = r\frac{dn_2}{dT} \qquad [6]$$

giving

$$r(l_1 - l_3) = (l_4 - l_2) \qquad [7]$$

This could of course be rewritten as

$$r = \frac{(l_4 - l_2)}{(l_1 - l_3)} \qquad [8]$$

Thus, for an optical device satisfying this result, variations in refractive index in the different transmissive materials will cancel each other out with the result that the total optical path difference of the device will remain constant with temperature. Thus, the invention provides a temperature stable device.

It is clear that satisfying these equations places some constraints on the possible lengths l_1, l_2, l_3 and l_4, but in practice there remain enough degrees of freedom to obtain a workable design.

In practice, the optical effect called for will set the optical path difference, and one of the path lengths will be set by the physical arrangement of the device. The ratio r is a constant, meaning that equations 1 and 7 must be solved for a fixed $l_1 + l_2$. Thus, there are sufficient variables to satisfy the necessary conditions.

Figures 2 and 3 show a suitable interface between silicon and silicon nitride waveguides. Referring to Figure 2, a silicon substrate 100 is provided with an oxide layer 102 thereon, on top of which is provided an epitaxial silicon layer in which a waveguide 104 is formed with an end face 110. A further oxide (or other dielectric) layer 106 is deposited over the oxide layer 102 adjacent the end face 110, and a nitride layer 108 is then provided over the layer 106 adjacent the end face 110. The structure

illustrated may be fabricated by the use of photolithographic techniques with masks defining the areas in which the layers 106 and 108 are deposited. Light escaping the end of the ridge waveguide 104 will thus enter the nitride layer 108.

Figure 3 shows a further refinement of the arrangement of Figure 2. It can be seen that the end 112 of the silicon waveguide 104 is angled so as to suppress back reflections. Likewise, the beginning of the nitride waveguide is angled, by virtue of its being formed adjacent the end of the silicon waveguide ridge.

A specific embodiment will now be worked through using silicon and silica as the transmissive media.

Typical values of the physical parameters are;

Silicon: $n_1 = 3.5$ $\quad \frac{dn_1}{dT} = 2x10^{-4}$

Silica: $n_2 = 1.5$ $\quad \frac{dn_2}{dT} = 1.1x10^{-5}$

Thus, to design a Mach Zehnder interferometer with an optical path difference of 15μm, we have;

$$15 = n_1 l_1 + n_2 l_2 - n_1 l_3 - n_2 l_4$$

$$15 = 3.5(l_1 - l_3) + 1.5(l_2 - l_4)$$

$$0 = 2 \times 10^{-4}(l_1 - l_3) + 1.1 \times 10^{-5}(l_2 - l_4)$$

$$0 = 200(l_1 - l_3) - 11(l_4 - l_2)$$

$$\frac{200}{11} = \frac{l_4 - l_2}{l_1 - l_3}$$

So $$l_1 - l_3 = -0.63\mu m$$

$$l_2 - l_4 = 11.47\,\mu m$$

This shows that the interferometer can be designed with either l_1 or l_4 as zero.

Figure 4 shows an arrayed waveguide grating. Several waveguides 120, 122, 124, 126 depart from a coupler region 128, follow paths with different path lengths, and recombine at a second coupler region 130. This can be designed using an analogous procedure. It is simplest to begin with the first pair of waveguides, and infer the dimensions of the remaining waveguides by working from the dimensions of the adjacent guide. For a grating with a wavelength spacing of 2nm, a suitable waveguide length difference will be 40μm.

So:

$$40\mu = 3.5(l_1 - l_3) - 1.5\frac{200}{11}(l_1 - l_3)$$

$$l_1 - l_3 = -1.68\,\mu$$

$$l_2 - l_4 = 30.6\,\mu$$

It is then a straightforward procedure to calculate values for l_5, l_6 etc based on the chosen values of l_1 to l_4.

CLAIMS

1. An integrated optical device comprising at least a first and a second associated optical pathway, at least the first pathway including at least two sub-sections of a first and a second different transmissive material, the different materials exhibiting a different temperature dependence of refractive index, the lengths of the pathways and of sub-sections being selected such that the device is substantially temperature insensitive.

2. An integrated optical device according to claim 1 wherein the second pathway also includes a sub-section of a different transmissive material.

3. An integrated optical device according to claim 1 or claim 2 wherein one of the first or second materials is silicon.

4. An integrated optical device according to any preceding claim wherein one of the first or second materials is silicon nitride.

5. An integrated optical device according to any preceding claim wherein one of the first or second materials is SiO_2.

6. An integrated optical device according to any preceding claim wherein each pathway includes only two sub-sections.

7. An integrated optical device according to any preceding claim including two sub-sections on two pathways.

8. An integrated optical device according to any preceding claim wherein the ratio of the difference in length of sub-sections formed

of the first material to the difference in length of the second material is equal to the ratio of the respective refractive index gradients with temperature of the materials used.

9. An integrated optical device according to any preceding claim integrated as a silicon or silicon on insulator chip.

10. An integrated optical device according to any preceding claim being an interferometer.

11. An integrated optical device according to any preceding claim being an arrayed waveguide grating.

12. An integrated optical device substantially as herein described with reference to and/or as illustrated in the accompanying drawings.

Fig 1

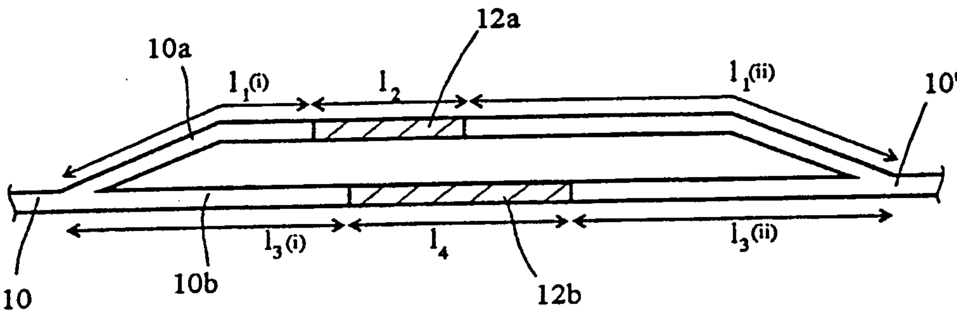

12a
10a
l_1(i)
l_2
l_1(ii)
10'
l_3(i)
l_4
l_3(ii)
10
10b
12b

Fig 2

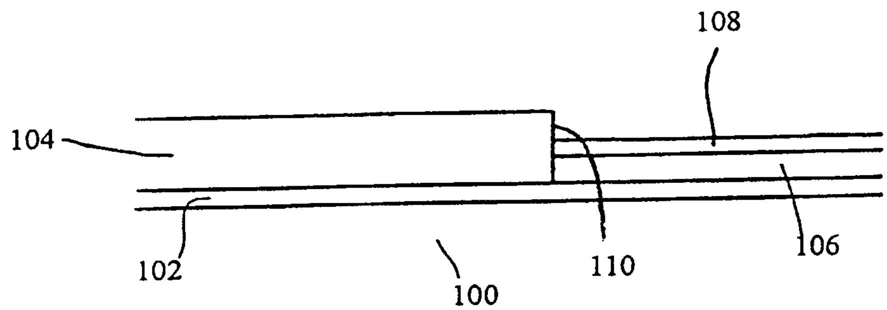

108
104
102
100
110
106

Fig 3

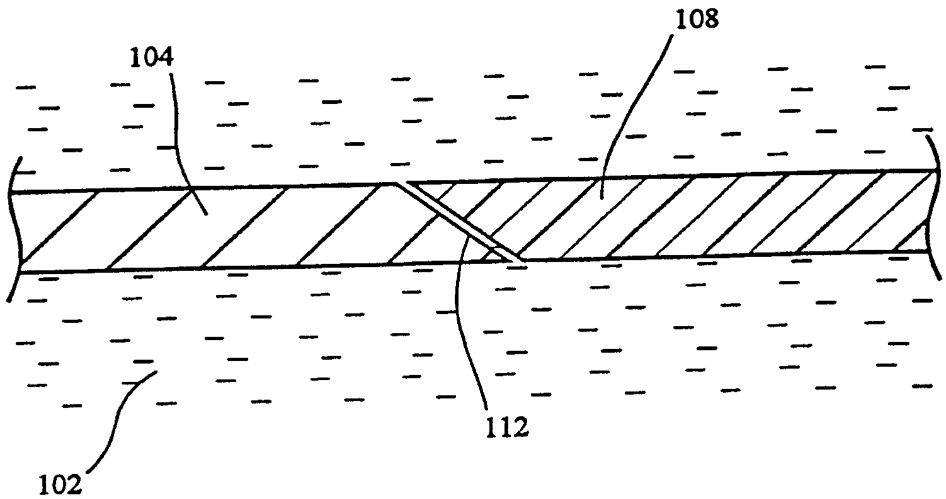
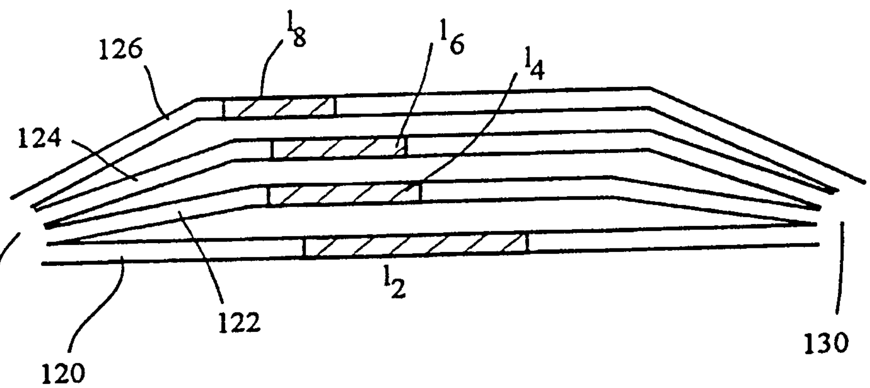


Fig 4



INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/01946

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B6/124

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	US 5 799 118 A (OGUSU MASAHIRO ET AL) 25 August 1998 (1998-08-25) column 7, line 14 - line 67 column 8 -column 9 column 10, line 1 - line 58 figures 10-17 ---	1,2,5-7, 10,11
A	TANOBE H ET AL: "TEMPERATURE INSENSITIVE ARRAYED WAVEGUIDE GRATINGS ON INP SUBSTRATES" IEEE PHOTONICS TECHNOLOGY LETTERS, vol. 10, no. 2, 1 February 1998 (1998-02-01), pages 235-237, XP000733815 ISSN: 1041-1135 the whole document -----	1,8,10, 11

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
5 October 1999	12/10/1999

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Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5799118 A	25-08-1998	JP 9043440 A	14-02-1997